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Reviewed Paper

Effects of Layer Orientation on the Multiaxial Fatigue Behavior of Additively Manufactured Ti-6Al-4V

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Abstract

Additive manufacturing (AM) allows for fabrication of components with complex geometries that cannot be fabricated using conventional manufacturing techniques. These components are often subjected to multiaxial stress states due to their typically complex design accompanied by residual stresses and/or multiaxial external loading. Therefore, understanding the fatigue behavior of AM materials under multiaxial-type loadings is necessary for ensuring reliable in-service component performance. In this study, the effects of layer orientation on the multiaxial fatigue behavior of Ti-6Al-4V fabricated via a laser-powder bed fusion (L-PBF) process was investigated. Tubular thin-walled multiaxial specimens were fabricated in vertical and diagonal orientations with respect to the build plate. Specimens were tested under axial, torsional, in-phase axial/torsional, and 90° out-of-phase axial-torsional cyclic loadings. Upon failure, the crack orientation of vertical and diagonal specimens was correlated to the type of loading, which illustrated the failure mechanism of L-PBF Ti-6Al-4V and justified the variations in the fatigue lives of specimens.

Keywords: Additive Manufacturing, Failure Mechanisms, Multiaxial Fatigue, Titanium.

Introduction

At its core principle, additive manufacturing (AM) technology allows for the incorporation of 3D computer aided designs into solid parts by melting and joining the feedstock material in a layer-by-layer manner [1–3]. The most commonly used AM process is laser-based powder bed fusion (L-PBF) [3–7], whose process consists of applying a layer of metallic powder over a substrate and melting the powder in a pre-determined section to create the first layer of part. This process is repeated until the part is completed [3]. Some inherent disadvantages of L-PBF process, also found in other metal AM techniques, include rough surface finish and the presence of tensile residual stresses, as well as internal defects such as lack of fusion (LOF) and porosity [6–8]. Microstructural characteristics, such as grain size, morphology, and orientation, are also influenced by the thermal history (e.g. cooling rate, reheating, etc.) experienced by parts during fabrication [7,8]. In addition, depending on the layer orientation (i.e. the build orientation with respect to a build plate), parts can experience different thermal histories, which subsequently affect morphology and direction of manufacturing-induced defects [7,9,10].

Recent studies [9–12] have focused on the effects of layer orientation on mechanical properties of several AM materials under uniaxial quasi-static and fatigue loadings. Bača *et al*. [10] investigated the fatigue behavior of direct metal laser sintering Ti-6Al-4V, and demonstrated that for all stress amplitude levels employed, the vertically-fabricated specimens had considerably shorter fatigue resistance than the horizontal specimens. However, several studies have found minimal effect of the layer orientation on mechanical behavior of AM metals [13,14]. For example, Torries *et al*. [13] investigated the effect of layer direction on the fatigue performance of L-PBF Ti-6Al-4V, and reported similar results for the horizontal, vertical and diagonal specimens under the same surface conditions (i.e. polished). Minimal differences in fatigue lives were attributed to low defect density. Based on these findings, it is suggested that further studies regarding layer orientation effects under more complex loadings are necessary.

Due to complex part geometry required for given applications, AM metallic parts are often subjected to multiaxial cyclic loading. In some cases, even under simple uniaxial loading, parts may experience multiaxial state of stresses. Fatemi *et al.* [6] recently investigated the effects of surface roughness (i.e. as-built and machined) on the multiaxial fatigue behavior of L-PBF Ti-6Al-4V under axial, torsion, and in-phase (IP) loadings. It was shown that surface machining improved the overall fatigue resistance of L-PBF Ti-6Al-4V under the aforementioned loadings. It was also found that the fatigue data for different surface roughness conditions correlated well with the maximum principal stress failure criterion, due to the materials brittle behavior. However, failure on the maximum principal stress or strain plane is not typical in titanium alloys. Previous studies [6,15–17] have demonstrated that failure of wrought titanium alloys is dominated by the maximum shear stress or strain plane. This failure mode is often explained by their ductile behavior allowing cracks to nucleate from slip planes. For brittle materials, such as L-PBF Ti-6Al-4V, cracks tend to originate from un-melted powder particles, LOF, or porosity [6,18,19].

To the best of the authors' knowledge, no research has been conducted on the multiaxial fatigue behavior of AM parts considering the influence of layer orientation. Therefore, in this study, the effects of layer orientation on the microstructural characteristics, mechanical failure modes, and multiaxial fatigue behavior of Ti-6Al-4V fabricated via L-PBF are investigated. The loadings include under axial, torsional, IP, and 90° out-of-phase (OP). Major findings and fatigue life correlation based on different failure criteria are presented.

Experimental Procedure

Gas-atomized Ti-6Al-4V Grade 23 powder with a particle size of 15-45 μm, manufactured by LPW Technology, was used to fabricate specimens via L-PBF process using an EOS M290 system. The default process parameters were employed, which include 280 W laser power, 1200 mm/s travel speed, 100 mm stripe width, 140 μm hatch spacing, 67° hatch rotation, and 30 μm layer thickness. The size and geometry of the tubular multiaxial thin-walled specimens, designed in accordance to ASTM E2207-15 standard [20], is depicted in Fig. 1. Specimens were fabricated in vertical, and diagonal (i.e. 45° from to the build plate) orientations. Stress relieve heat treatment was performed at 704 °C (1300 °F) under argon atmosphere for 1 hour followed by furnace cooling. Specimens were then removed from the build plate, and their gage section was lightly polished to remove residual powder prior to testing. No post-processing machining was carried out on these specimens. The microstructure was characterized by cutting the gage section of specimens in the longitudinal and radial directions. In the case of the diagonal specimens, the longitudinal dissection was performed along the supported side (i.e. down-skin). The cut samples were then polished and etched with Kroll's reagent.

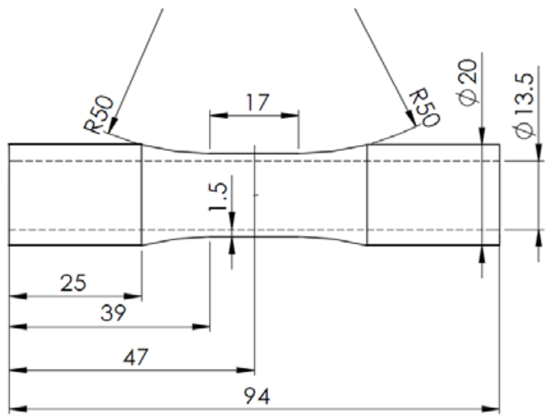


Fig. 1. Tubular multiaxial specimen with uniform gage section per ASTM standard E2207-15 [20]. All dimensions are in mm.

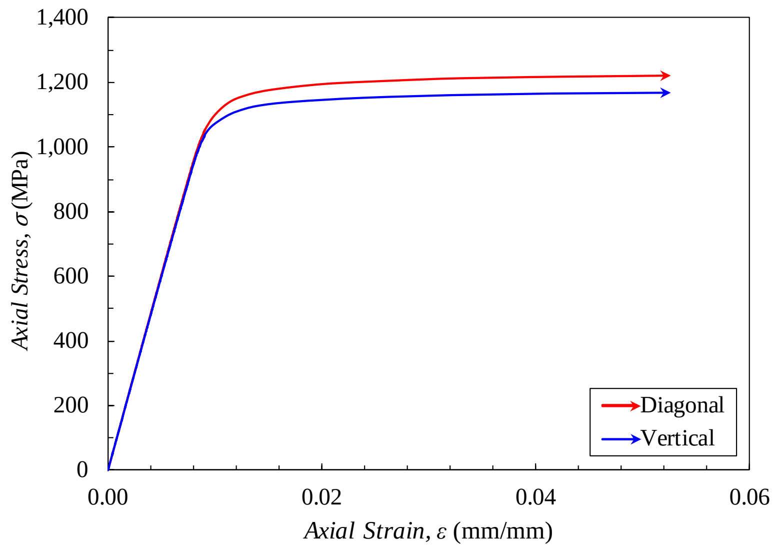
Monotonic and fatigue tests were conducted using a MTS 809 axial/torsion closed-loop servohydraulic test system equipped with 100 kN axial force, and a 1100 N m torsional force load capacity. Displacement- and rotation-controlled mode at 0.1 mm/min and 0.1 °/min were used in monotonic tension and torsion tests respectively. An axial/torsion mechanical extensometer was used to record strain values. Fully-reversed (R = -1) fatigue tests were carried in force and torque control modes using a tapered sinusoidal waveform signal. Force and torque control modes were used due to the fatigue deformation response of the material being fully elastic. The loading paths employed in this study were axial, torsional, IP, and OP. Depending on the type of loading, test frequency was adjusted (0.4 - 2 Hz) to minimize any strain rate effects. A duplicate test for each loading configuration was conducted to verify the consistency of the collected data.

Results and Discussion

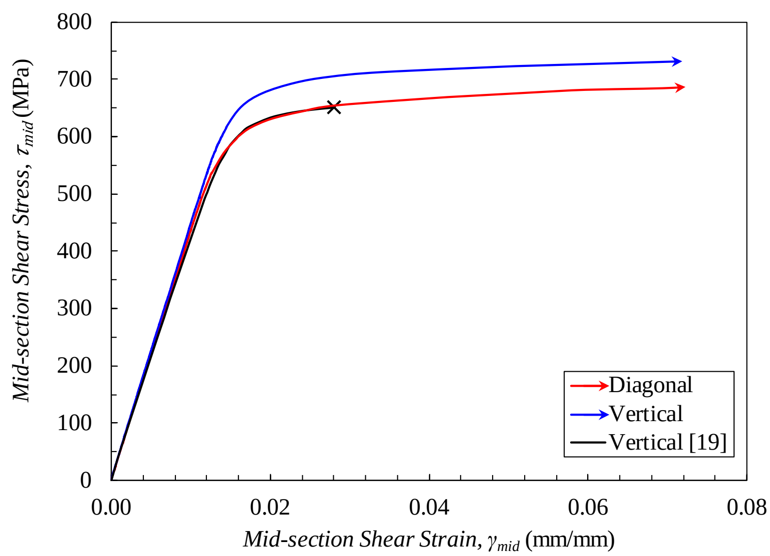
Monotonic Deformation

The monotonic axial and torsional stress-strain responses of the vertical and diagonal specimens are presented in Figs. 2(a) and 2(b), respectively. Strain was recorded up to the extensometer limits (i.e. curves ended with arrows); the extensometer was then removed and the test continued until final fracture. As shown in these figures, the layer orientation, with respect to the loading, influences the mechanical response of L-PBF Ti-6Al-4V.

Fig. 2(a) shows that the diagonal specimens have slightly higher yield stress (~ 55 MPa) as compared to vertical specimens, while both specimens seem to exhibit similar work hardening rates, retaining their near constant gap of 60 MPa. Furthermore, vertical specimens appeared to be more ductile as the displacement at final fracture was ~17% higher than the diagonal specimens (the values are not presented in the figures). Similar findings were reported for selectively laser melted and direct laser deposition AM Ti-6Al-4V studies [8,9,21], where it was concluded that layer orientation being parallel to the load (e.g. horizontal specimens) resulted in higher yield and ultimate tensile strengths, and lower elongation to failure. It is worth mentioning that L-PBF specimens, regardless of layer orientation, exhibited relatively higher yield and ultimate stress response as compared to wrought Ti-6Al-4V [6,22]. This was attributed to the higher cooling rate in AM process, which leads to the formation of finer martensitic α' laths.



(a)



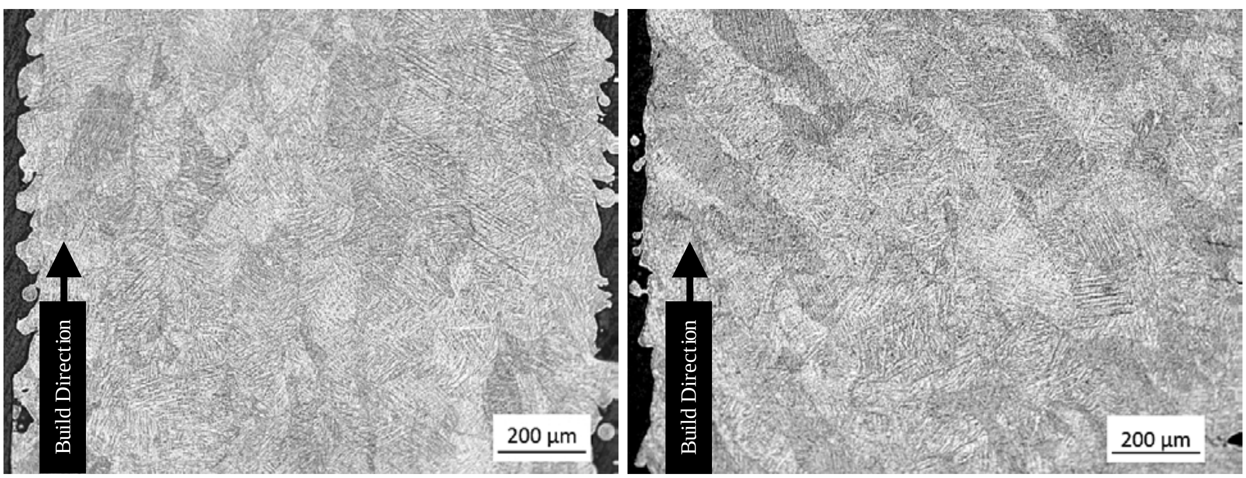
(b)

Fig. 2. Monotonic stress-strain curves of L-PBF Ti-6Al-4V specimens under (a) axial and (b) torsion loading.

As is seen in Fig. 2(b), the torsional behavior is also affected by the layer orientation, where the vertical specimen had slightly higher yield and ultimate shear strengths than the diagonal ones by ~65 MPa. The vertical specimens had increased shear ductility due to final fracture, having

~10% greater angle of rotation than the diagonal specimens. In Fig. 2(b), the torsional behavior of the vertical and diagonal specimens are also compared to a recent study for L-PBF Ti-6Al-4V [19]. It can be seen in this figure that the mid-section shear stress-strain responses in [19] are similar to the diagonal specimen in the present study, but with significantly less ductility. This could be attributed to the different AM system and process parameters used for specimen fabrication.

The anisotropy in elongation to failure under both axial and torsional loadings was consistent with the existing literature, where loading direction being parallel to the columnar prior β grains (e.g. vertical specimen under monotonic axial loading) resulted in higher elongation [21]. Epitaxial grain growth orientation of the vertical and diagonal specimens is presented in Figs. 3(a) and 3(b), respectively. The observed anisotropy in ductility may be due to the formation of primary α on prior β grain boundaries, which are subjected to accelerated damage under larger principal tensile stress (i.e. mode I or crack opening mode) component for diagonal specimens. The variations in yield stress and ultimate tensile strength (i.e. ~5% variance) may be justified by α' lath thickness differences and overall texture of the specimens stemming from their thermal histories [23]. The variations in thermal histories, i.e. cooling rates, is due to the changes in the thermal conduction capacity or volume of the material underneath the molten metal layer caused by sample orientation with respect to the substrate [7].

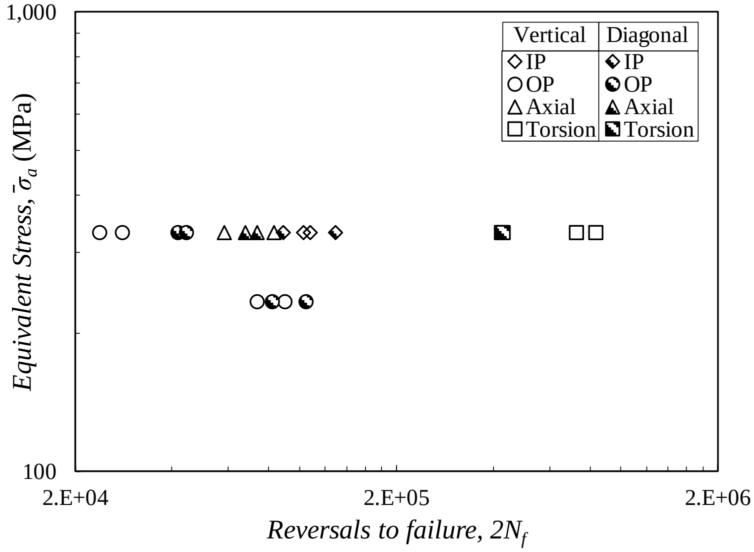


(a) (b)

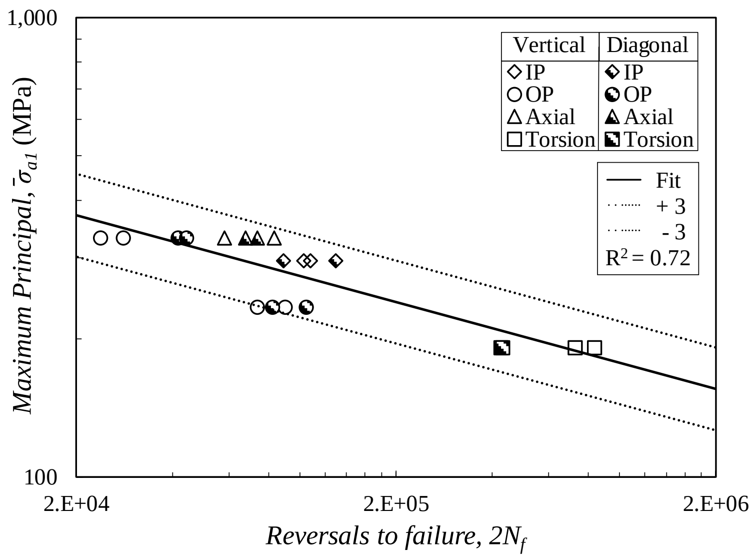
Fig. 3. Microstructure of L-PBF Ti-6Al-4V built in (a) vertical and (b) diagonal orientations.

Fatigue Behavior

Two equivalent stress amplitude levels (331 and 234 MPa) based on von Mises equivalent stress were selected for fatigue testing as the results were expected to be in between the short and long cycle regime. The stress-life results of vertical and diagonal specimens under axial, torsional, IP, and OP loading tests are presented Figs. 4(a) and 4(b). It is important to emphasize that the shear stress at the surface was used to analyze the fatigue behavior of torsion and axial/torsional tests. As seen in Fig. 4(a), when using von Mises equivalent stress criterion for axial, torsional, IP, and OP loadings, the fatigue lives were expected to be similar given that an equivalent stress amplitude of 331 MPa was used. However, results show a fatigue life variance with a factor of 26 when all loadings are considered. This is attributed to this criterion typically providing better fatigue life correlation for ductile materials, and L-PBF Ti-6Al-4V having a brittle behavior and tensile failure mode [6,18]. This also agrees with the findings by Fatemi *et al.* [6], and the final crack orientation of the specimens being oriented along the maximum principal plane. Further explanation on the damaging effects of OP loading can be found in [18].



(a)



(b)

Fig. 4. Correlation of fatigue test results of L-PBF Ti-6Al-4V using (a) von Mises equivalent stress, and (b) maximum principal stress criterion.

Under OP loading and an equivalent stress amplitude of 331 MPa, it can be seen that the diagonal specimens had longer fatigue life than the vertical specimens; while, for torsional loading, the results were vice versa. For OP loading and an equivalent stress of 234 MPa, the effects of layer orientation were negligible. For IP and axial loadings, fatigue lives were similar for the diagonal and vertical specimens. Differences between OP and torsional, IP and axial, at 331 MPa stress level can be attributed primarily to the layer orientation with respect to the maximum principal stress plane under each loading condition. For OP loading, the maximum tensile and maximum shear stress plane is oriented at 0°. Therefore, in the case of vertical specimens, the layers are oriented along the maximum tensile stress plane, thus the stress concentration due to surface roughness causes the crack to propagate directly across the grains without much resistance. This in turn, may shorten the fatigue life remarkably. In the case of torsional loading, the layers of the diagonal specimens are oriented along the maximum tensile stress plane; therefore, the stress concentration due to the surface roughness will cause failure to occur along this plane. The maximum tensile stress plane is also oriented at 0° or 90° with respect to the prior β grain boundaries, which may also contribute to the reduced fatigue life. This is due to the primary α on the prior β grain boundaries exhibiting less resistance to crack propagation when the maximum tensile stress is perpendicular to the prior β grain boundaries [21].

Since it was determined that failure occurred along the maximum principal plane (i.e. tensile mode), the maximum principal stress amplitude was correlated to fatigue life, as presented in Fig. 4(b). As can be seen in this figure, the principal stress versus fatigue life is appropriately correlated and the data falls within the scatter bands of a factor of three from the fit. Although the layer orientation is influential in terms of fatigue performance, the maximum principal stress criterion can address the observed discrepancies. It can also be observed that, under OP loading at 234 MPa stress amplitude level, the data falls on the lower scatter band, which indicates that the maximum principal stress may not be the appropriate criterion for L-PBF Ti-6Al-4V. Therefore, further studies are needed to obtain more appropriate critical plane criterion to improve the overall results.

Conclusions

This study examined the effects of layer orientation on the monotonic deformation and fatigue behavior of L-PBF Ti-6Al-4V under several types of loading including axial, torsional, in-phase (IP) and 90° out-of-phase loading (OP) axial-torsional. The following conclusions can be inferred from the experimental results and analysis:

1. Comparison of vertical and diagonal specimens under monotonic axial and torsional loadings indicated the deformation and failure behavior of L-PBF Ti-6Al-4V is affected by the layer orientation (i.e. microstructure and defect orientation) with respect to the maximum principal plane. Implying that, when the maximum principal loading is parallel to the grains, the stress response will decrease and ductility will increase.
2. Under different combination of axial/torsional fatigue loadings, the layer orientation plays an important role in the resultant fatigue resistance. For example, diagonal specimens offered superior results under OP loading when compared to the vertical specimens, while vertical specimens outperformed the diagonal ones under torsional loading.
3. The von Mises stress criterion was not able to correlate fatigue results as the failure mode of L-PBF Ti-6Al-4V was found to be along the maximum principal plane, and not the maximum shear stress plane.
4. The maximum principal stress criterion presented acceptable fatigue life correlation due to the brittle behavior of L-PBF Ti-6Al-4V, where all the data was correlated within a scatter factor of three.

Acknowledgements

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